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Behre, Karl-Ernst; Plicht, Johannes van der

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Towards an absolute chronology for the last glacial period in Europe: radiocarbon dates from Oerel, northern Germany

Karl-Ernst Behre[1] and Johannes van der Plicht[2]

[1] Niedersächsisches Institut für historische Küstenforschung, Viktoriastrasse 26/28, W-2940 Wilhelmshaven, Federal Republic of Germany
[2] Centrum voor Isotopen Onderzoek, Nijenborgh 4, NL-9747 AG Groningen, The Netherlands

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Abstract. Radiocarbon dates from the terrestrial Weichselian standard profile of Oerel are presented. The end of the Early Weichselian (WE IV, corresponding to isotopic stage 5a) is dated by two independent analyses to around 61 000 years B.P. The two subsequent interstadials, Oerel and Glinde, which have been described from this locality in an earlier publication, are dated to ca. 58 000 - 54 000 B.P. and 51 000 - 48 000 B.P., respectively. The dates of both interstadials are in good agreement with the chronology available from the deep sea record. The chronology of the younger part of the Pleni-Weichselian is briefly reviewed.

Key words: Radiocarbon dates - Weichselian chronology - palaeoclimatology

Introduction

The chronology of the last glacial period (Weichselian or Würmian in Europe) has been approached in various ways: the deep sea timescale (Emiliani 1955, Martinson et al. 1987), which is regarded as the most reliable, the astronomic approach, which, though theoretical, has gained increasing support during recent years (Berger 1978), and the terrestrial record (Behre 1989), where the radiocarbon method can be applied over a considerable time span.

In the deep sea cores the last interglacial-glacial cycle is characterised by two marked interstadials (isotopic stages 5c and 5a) following the Eemian interglacial (5e). Several terrestrial records show also two well developed interstadials, represented as peat or lacustrine sediments, on top of Eemian deposits.

The correlation of the land and sea chronologies has been subject of several studies. With respect to the Early Weichselian two alternative proposals have been made (Woillard 1979, Woillard and Mook 1982):
(1) the two long and temperate interstadials, St. Germain I and St. Germain II, above the Eemian in the long terrestrial record of Grande Pile, eastern France, and found also in several other sites in the Alpine foreland, correspond to the deep sea stages 5c and 5a. They form, together with the Eemian below them, the last interglacial cycle but cannot be correlated with the Early Weichselian interstadials in and around the Netherlands. They have still to be recorded in northern Central Europe. A hiatus between the Eemian and the Amersfoort/Brörup complex must therefore be assumed.
(2) the temperate interstadials St. Germain I and II correspond to the cooler interstadials Amersfoort/Brörup and Odderade in northern Central Europe. This requires the assumption of a steep climatic gradient during the Early Weichselian. This hypothesis restricts the number of major Early Weichselian interstadials in Europe to two, corresponding to those represented in the deep sea isotopic stages 5c and 5a.

The site at Oerel, northern Germany

The stratigraphy at Oerel, northern Germany (53°59' N, 9° 04' E), has contributed decisively to the solution of the chronological problems referred to above (Behre and Lade 1986, Behre 1989). For the first time in northern Central Europe, an uninterrupted continuous sequence has been recorded that extends from the Eemian to the Pleni-Weichselian and includes four interstadials, represented by peat and separated from each other by sand layers (Fig. 1). Some of the organic sequences are within the range of the radiocarbon dating method. These radiocarbon results, which are presented below, contribute significantly towards attaching an absolute chronology to the terrestrial Weichselian stratigraphy.

Pollen diagrams showed that the two lower interstadials at Oerel represent two long forested periods that correspond to the Amersfoort/Brörup complex and the Odderade, respectively. The two upper interstadials, newly described as Oerel and Glinde, show a quite different, decidedly non-forested vegetation.

All interstadials, as well as the Eemian, cover large areas in the Oerel basin. On the basis of extensive corings and also pollen analytical investigations, it is concluded that an undisturbed deposition is available here and, furthermore, the possibility of major hiatuses can be discounted with confidence.

Offprint requests to: K.-E. Behre

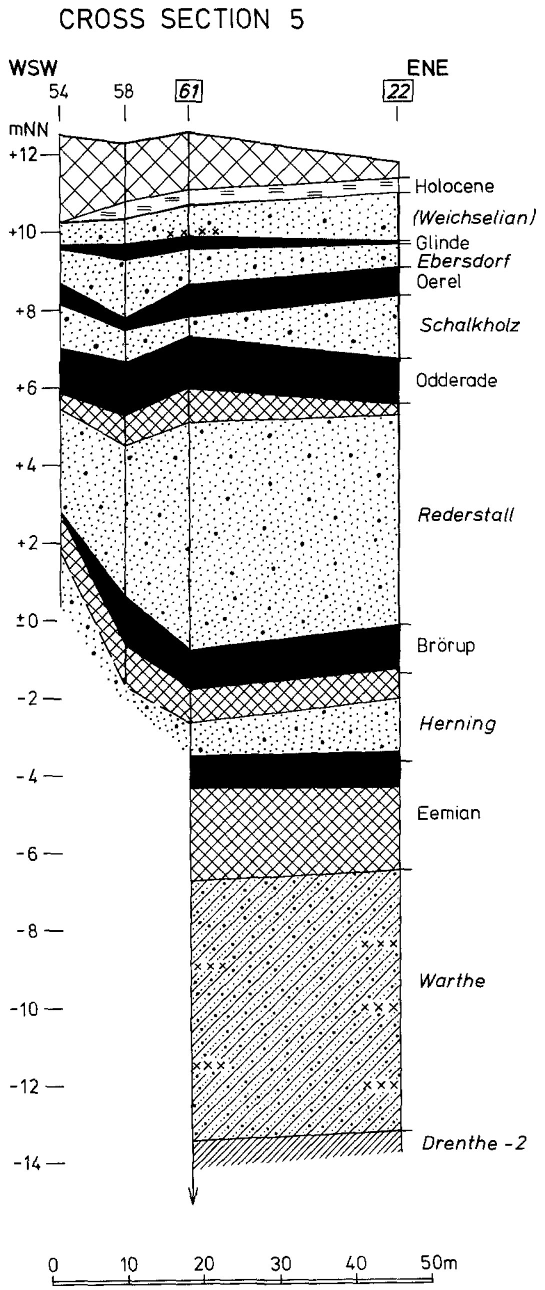


Fig. 1. Cross section 5, Oerel (vertical exaggeration x5). The numbers on top indicate corings; material from coring no. 61 was used for ^{14}C dates.

The results from Oerel confirm that there were only two major Early Weichselian interstadials in Europe and suggest that further forested interstadials in northern Central Europe, as demanded by the first correlation hypothesis outlined above, are highly improbable. This means that the second hypothesis, i.e. the correlation of St. Germain I with Amersfoort/Brörup and deep sea stage 5c, and St. Germain II with Odderade and deep sea stage 5a can now be regarded as proven. Additional supporting evidence for the lack of an hiatus between Eemian and Amersfoort/Brörup has been provided by several recent investigations of Early Weichselian sites (Menke and Tynni 1984, Jastrzebska-Mamelka 1985). This is in agreement with the classic sites of Grande Pile, already mentioned, and the south European site of Les Echets (de Beaulieu and Reille 1984), Valle di Castiglione (Follieri et al. 1988), Tenaghi Philippon (Wijmstra 1969) and Padul (Pons and Reille 1988), as well as the pre-Alpine sites (Grüger 1979, Welten 1982). The boundary between Early and Pleni-Weichselian is placed at the end of the Odderade interstadial (cf. Behre 1989, p. 36).

The site, Oerel, also provides evidence, in the form of the Oerel and Glinde interstadials, towards the resolution of the lower part of the Pleni-Weichselian. The pollen analytical results provide clear evidence that these interstadials are not equivalent to the earlier described Dutch interstadials (Moershoofd, Hengelo, Denekamp) which must be younger.

Fortunately, all interstadials of the Oerel series are from pure peat deposits and, to a large extent, consist of *Sphagnum*. This provided ideal material for reliable radiocarbon dates.

The radiocarbon dates

While several cores from Oerel were used for pollen diagrams, material for the ^{14}C analyses was taken mainly from the standard profile, core no. 61 (Fig. 1). All samples were analysed by means of the AAA (Acid/Alkali/Acid) technique (Mook and Streurman 1983). The available radiocarbon ages are shown in Table 1. They are reported in B.P. (Before Present), i.e. prior to A.D. 1950, and are corrected for isotopic fractionation to $^{13}{}_{PDB}$= -25 (Mook and Waterbolk 1985).

In a few cases, ages were obtained for both the alkaline extract and for the residual fraction. The extracts usually show a slightly younger age than the residual fraction. The extract represents the humic substances that are formed in situ as a result of humification of fresh organic material.

All samples were measured in the Groningen large volume, high precision counter (Tans and Mook 1978). With this counter - provided there is enough material available for analysis - very old samples (up to 10 half lives) can be measured. The background of this counter corresponds to a radiocarbon age of 61 600 B.P. (Rozanski et al. 1991). The errors quoted in the table correspond to 1 σ (68% confidence level). Where the measured activity of the sample is less than twice the standard deviation of the measurement, the value of 2 σ is added to the measured activity (Olsson 1989). This result is then converted to ^{14}C years B.P., which is regarded as a lower value for the particular sample (cf. GrN-17531, 17532 and 17534; identified as Odderade, Table 1).

On the basis of the ^{14}C results, we conclude that the Glinde and Oerel interstadials date to 48-51 and 54-58 ka B.P., respectively. The top of the Odderade has a radiocarbon age of ca. 61 ka. The latter result corresponds well with an previously obtained date from core 46, Oerel. The top of the well defined Odderade section from this core is dated to 61 600 +3000/-2200 B.P. (GrN-12429).

Comparison with other Weichselian sites

Until recently, there have been few reliable ^{14}C dates from terrestrial sites relating to the lower part of the Weichselian

Table 1. Radiocarbon dates from Orel (core 61)

	Depth (cm)	Lab. No. GrN-	Age in years BP Residue	Extract	
Glinde interstadial	274-282	13798	51550 ±550		Sedge peat
	274-282	13799		48700 +3200/-2300	Sedge peat
	282-290	13800	48720 ±360		Sedge peat
	282-290	13801		47000 +2500/-1900	Sedge peat
	280-295	12372	50200 ±700		Sedge peat
Oerel interstadial	397-450	12373	55400 ± 900		Sphagnum peat
	400-410	17533	53500 +2900/-2100		Sphagnum peat
	410-420	17530	55900 +4000/-2700		Sphagnum and brown moss peat
	410-421	13037	57300 +1900/-1600		Sphagnum and brown moss peat
	420-460	14183	57700 ±1300		Brown moss and Sphagnum peat
	420-460	14465		57000 +3500/-2500	Brown moss and Sphagnum peat
Odderade interstadial	535-545	12656	60800 +2300/-1800		Sphagnum and brown moss peat
	585-595	17534	>55560		Sphagnum and brown moss peat
	592-607	17531	>54850		Sphagnum and sedge peat
	607-635	17532	>54200		Sphagnum and brown moss peat

(i.e. > 40 000 years B.P.) in Europe. Here, only those dates are considered that come from reliable stratigraphic positions confirmed by pollen analytical evidence. An important site in this regard is the classic profile of Grande Pile (Woillard and Mook 1982) though, in that profile, there are only two dates older than 40 000 B.P. Other dates were provided by Grootes (1977) and Welten (1982), most of them, like those from Oerel, coming from the Groningen Laboratory (W.G. Mook).

Starting with the oldest dates, which are close to the limits of the ^{14}C method, there are the two dates for the top of the Odderade-interstadial: 60 800 +2300/-1800 B.P. from the standard profile OE 61 and an earlier obtained date 61 600 +3000/-1800 B.P. from the profile OE 46, 35 m further south. These dates lie between the date from Grande Pile (69 500 B.P., Woillard and Mook 1982) and the thermal diffusion dates of Grootes (1977) which, as a whole, are younger. The oldest ^{14}C date published by Welten (1982) from the Alpine foreland is 61 300 ± 1000 B.P. from Dürnten II. Welten regards it as corresponding well with the end of the Early Weichselian though according to his pollen diagram it lies between Brörup and Odderade. Another old date from the northern Alps is provided by Grüger (1979) from Samerberg where the beginning of the Odderade interstadial is dated to 72 300 B.P. Pons and Reille (1988) published a ^{14}C date of 63 500 B.P. from the middle part of St. Germain II (Odderade) at Padul, S. Spain, which supports the view that the Odderade lies between 72 and 61 ka B.P.

Apart altogether from the ^{14}C evidence, some consideration must also be given to the duration of the Early Weichselian interstadials that lies beyond the limit of the radiocarbon method.

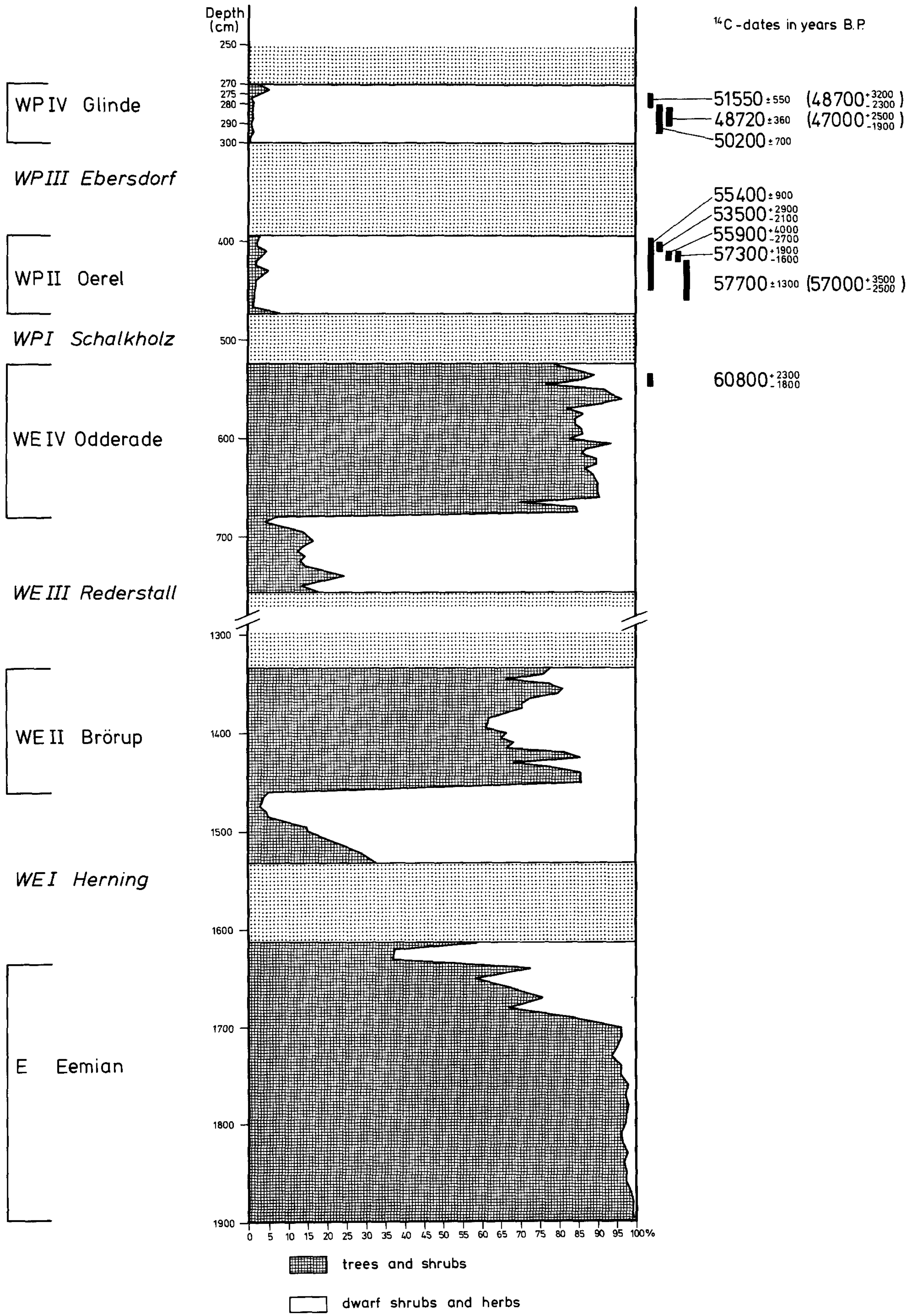
In most of the complete profiles from northern Central Europe, the Brörup (always including Amersfoort) as well as the Odderade deposits show a remarkable thickness, often almost as great as that of the Eemian below. Both these interstadials must have been of approximately similar and of long duration. Where the interstadial deposits are formed as peat, the thickness of each interstadial may exceed one metre and reach up to 1,60 m (at Zgierz-Rudunki, Jastrzebska-Mamelka 1985). It should be borne in mind that these peats have been subjected to the pressure from several metres of overlying minerogenic sediments over a long period. Considering the present thickness of these compressed peats, a period of 5000-10 000 years for the duration of both the Brörup and the Odderade would seem appropriate. This fits in well with the evidence from the deep sea record.

A direct estimation has recently been made for the duration of the Brörup interstadial by Grüger (published in Behre 1989, p. 38, also Grüger, in press). By means of confirmed annual laminations in parts of the diatomite layers of the Rederstall profile, northern Germany (Menke and Tynni 1984), he was able to estimate the length of the Brörup interstadial to be around 7600 years and with the minimum and maximum duration of 5800 and 10 500 years, respectively. The diatomite layers of Rederstall attained a surprising 10.4 m thickness, all of which was deposited in the Brörup interstadial.

The duration of the Eemian has been estimated to be ca. 11 000 years by counting annually laminated diatomite deposits at Bispingen, northern Germany (Müller 1974).

The Oerel interstadial has already been correlated with the third interstadial in the Alpine foreland on the basis of its stratigraphic position and the pollen analytical evidence (Behre and Lade 1986, Behre 1989). This third interstadial is clearly represented in Samerberg (Grüger 1979) and in several profiles from Switzerland where Welten (1982) called it Dürnten. Welten provided a ^{14}C date from the type locality, Dürnten, of 55 500 ± 550 years B.P. which represents a level just above the Dürnten interstadial. This date strongly supports the correlation with Oerel, where the third (Oerel) interstadial is assumed to lie within the range 58 000 - 54 000 years B.P. on the basis of several ^{14}C dates (Table 1).

New investigations of the early Pleni-Weichselian at Les Echets (southeastern France, de Beaulieu and Reille 1989) show three minor interstadials after the end of St. Germain



Depth (cm)
250
270
275
280
290
300
400
500
600
700
1300
1400
1500
1600
1700
1800
1900
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100%
WP IV Glinde
WP III Ebersdorf
WP II Oerel
WP I Schalkholz
WE IV Odderade
WE III Rederstall
WE II Brörup
WE I Herning
E Eemian
¹⁴C-dates in years B.P.
51550 ± 550 (48700 +3200 -2300)
48720 ± 360 (47000 +2500 -1900)
50200 ± 700
55400 ± 900
53500 +2900 -2100
55900 +4000 -2700
57300 +1900 -1600
57700 ± 1300 (57000 +3500 -2500)
60800 +2300 -1800
trees and shrubs
dwarf shrubs and herbs

II. According to these authors, the first two (zones F7 and H) could be compared with Oerel and Glinde. In an earlier paper (Behre 1989), the Oerel interstadial was correlated with the Ognon II interstadial at Grande Pile. However, a new pollen diagram from there (Grande Pile XX), prepared by de Beaulieu and Reille, provides good evidence for a hiatus at the beginning of the Pleni-Weichselian in Grande Pile. The authors regard the 'interstadials' Ognon II and Ognon III of Woillard (1979), which are not reflected in all diagrams from Grande Pile, as resulting from reworked pollen of mesophilous trees during colder periods (de Beaulieu, personal communication 1992).

Until now, the pollen analytical evidence from Grande Pile provided no clear equivalent to the uppermost Glinde interstadial that has been ^{14}C dated to between 51 and 48 ka B.P. These dates, however, are close to the date of 49 800 B.P. obtained by Woillard and Mook (1982) for the peak in tree pollen in pollen zone 14 at Grande Pile which represents, according to Woillard 1978, the climatic amelioration of the Pile oscillation. Although the correlation of the Pile oscillation with the Glinde interstadial is tentative, it is supported by the existence of another amelioration in Grande Pile - the Goulotte oscillation below the Pile oscillation. This might be an equivalent to the Oerel interstadial as it is situated just above the first severe cooling in Grande Pile (stadial I of Lanterne II), a position comparable to the Oerel. In north-west Europe, the first sharp decline of temperature resulting in ice wedges, etc. occurred after the Odderade (= St. Germain II).

Considerable uncertainty is attached to the so-called Moershoofd interstadial or complex. It seems that most organic layers, with ^{14}C dates between 43 000 and 50 000 B.P. (reliable or not), are placed in this black box. The dates from the type site, Moershoofd, south-western Netherlands, are 46 250 ± 1500 and 43 500 ± 1000 B.P. (Zagwijn 1961, corrected dates from van der Hammen et al. 1967). Our knowledge of the Moershoofd is so limited that nobody is certain whether it represents a true interstadial with clear boundaries or whether it includes several slight oscillations. The various organic layers may also be local phenomena at places with slightly more favourable edaphic conditions for short periods. This is supported by pollen analysis where *Cyperaceae* normally reach 70-80% of total pollen (Zagwijn 1961, Kolstrup and Wijmstra 1977, Ran 1990). In contrast to this, the Glinde interstadial in Oerel has a well developed shrub or dwarf shrub tundra vegetation with average *Cyperaceae* values of only 44.5%. To sum up: the stratigraphical and pollen analytical evidence, as well as radiocarbon dates, show that the Glinde is a clearly delimited interstadial which precedes the Moershoofd, if the latter is valid at all.

Fig. 2. Core no. 61 from Oerel showing the radiocarbon dates and their position within the core. The curve of trees and shrubs versus dwarf shrubs and herbs is also shown. In the Glinde and Oerel interstadials, as well as in the stadials preceding the Odderade and the Brörup, *Betula* (= *B. nana*), *Salix* and *Juniperus* have been included in the dwarf shrubs, while, in the wooded periods, these genera (because of the presence of trees) probably represent shrubs and are therefore placed in the category trees/shrubs. Most of the tree and shrub pollen in WE I and WE III must be regarded as redeposited. Radiocarbon dates in brackets are from alkali extract of the same sample.

The sequence at Oerel ends with the Glinde interstadial but for completion some remarks about the upper part of the Pleni-Weichselian should be added. Apart from the Moershoofd, the better substantiated interstadials, Hengelo and Denekamp, have been described from several sites. Numerous ^{14}C dates from organic layers of the middle and upper part of the Pleni-Weichselian, most of them from the Netherlands or neighbouring regions, are available. Put together in a frequency graph, as for instance in van der Hammen et al. (1967) or Ran (1990), they show a continuous distribution with slight maxima at 28 000-32 000 (Denekamp), 36 000-39 000 (Hengelo) and 44 000-46 000 ('Moershoofd') BP.

With respect to the sites in the Netherlands, where most of the examples have been found, Vandenberghe (1985) presented a convincing explanation that took into account the local geomorphological conditions. He argued that the presence of peaty layers in this period is restricted to wet depressions where there was a local improvement of edaphic conditions. He considers that these conditions are temporary and are not necessarily of climatic significance, but have been facilitated by local geomorphological conditions. This seems certainly true for the 'Moershoofd' sites, while the Hengelo and Denekamp interstadials, which are better supported by pollen analytical results, seem to represent interstadials with distinct climatic improvements. It is striking, however, that evidence for the Hengelo and Denekamp interstadials are so rare outside the Netherlands. This might be explained by climatic conditions in that region which were such that the vegetation was particularly sensitive to minor climatic oscillations. The compilation of West (1977, Fig. 2) for Great Britain shows no evidence for a significant oscillation in this period apart from the Upton Warren interstadial, which is dated to ca. 42 ka B.P., and also the long record from Padul in Spain (Pons and Reille 1988) has no clear indication of climatic changes between Early and Late Weichselian. On the other hand, the radiocarbon dates from Grande Pile (Woillard and Mook 1982) suggest correlation of the phases of climatic amelioration recognised in that profile to Denekamp, Hengelo and perhaps Glinde (and Oerel) interstadials. Not only general climatic changes in western Europe but also changes in the climatic gradient must obviously be considered when attempting to explain these apparently conflicting strands of evidence.

Comparison with deep sea cores

The radiocarbon-based chronology of the Oerel and Glinde interstadials are in excellent agreement with the absolute chronology derived from deep sea cores. The results of high resolution chronostratigraphy by Martinson et al. (1987, Fig. 18) show distinct peaks in the delta ^{18}O curve between 58 and 54 ka, and 50 and 48 ka B.P., that correspond to the ^{14}C dates, 58 to 54 ka, of the Oerel interstadial and the ^{14}C dates, 48 to 51 ka, of the Glinde, respectively. Both belong to the lower part of isotopic stage 3 (see also Mangerud 1989).

In contrast to the Pleni-Weichselian, the dates from the end of the Odderade interstadial show some divergence. While the boundary between the isotopic stages 5a and 4 in deep sea cores is dated to 74 ka there are two independent and consistent dates from Oerel at ca. 61 ka B.P. As was

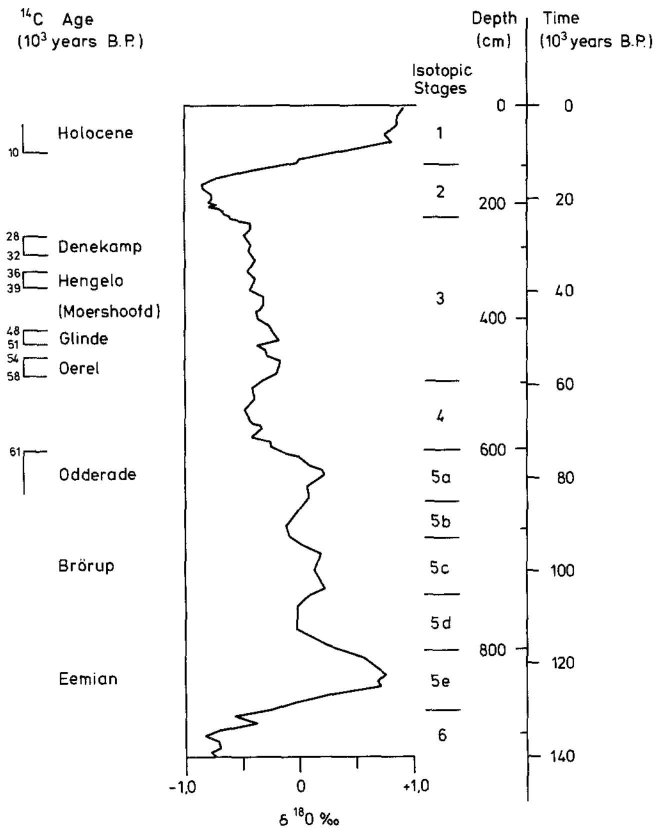


Fig. 3. Comparison of the $^{16}O/^{18}O$ deep sea record (after Martinson et al. 1987) with the radiocarbon chronology from terrestrial sites.

shown before, the ^{14}C-based terrestrial dates for this level are generally younger than the dates from the deep sea cores. Possible explanations for this divergence are offered below.

Discussion

The ^{14}C dates of the Oerel (58-54 ka B.P.) and Glinde interstadial (51-48 ka B.P.) must be regarded as fully reliable for two reasons: the dates lie very close together, sometime overlap within the interstadial and, furthermore, there is a satisfactory measure of agreement with the chronology based on deep sea cores.

Meaningful comparison with other terrestrial sites on the basis of pollen analytical results is difficult because comparable data are so limited. The Oerel interstadial may be compared with the Dürnten interstadial (equivalent to Samerberg 3) in the Alpine foreland and this is supported by the single date just before 55 500 B.P. from there (Welten 1982). The earlier assumption of a correlation of the Oerel interstadial with the Ognon interstadial has to be abandoned due to the new evidence that suggests that the latter represents reworked material.

While pollen analytical results that may be regarded as comparable with those of the Glinde interstadial are not yet available, the ^{14}C dates correspond well with the date of 49 800 +1500/-1300 from the Pile oscillation of Grande Pile (Woillard 1978, 1979). It may represent the same climatic improvement. More radiocarbon dates from that level of Grande Pile would be most desirable. This tentative correlation is supported by evidence for another rise in temperature between Pile and St. Germain II - the Goulotte oscillation - at Grande Pile. This follows the first severe cold phase, similar to what is recorded at the type site Oerel.

While the dates of ca. 61 ka B.P. for the end of the Odderade diverge from the deep sea chronology, comparable dates are available from terrestrial sites (Padul, Samerberg). The dates for the Early Weichselian obtained by Grootes (1977), based on ^{14}C-enrichment by thermal diffusion, are generally younger than other dates available from terrestrial sites. Closer examination of his results show that it is mainly the dates from the Odderade-type profile that are too young. It should be noted that the peat from the site in question is covered by only 5.5 m of pure medium-grained sand. It is our opinion that some contamination from the overlying layers cannot be excluded. For some of the other organic layers investigated by Grootes it is very difficult to decide whether they belong to the Brörup interstadial as indicated in his table or to the Odderade. If the latter is true, then most of Grootes' dates would fit quite well with the chronology as postulated on the basis of terrestrial material.

In comparing the absolute chronology of the terrestrial record with that based on deep sea cores, a good accordance can be demonstrated only for the Pleni-Weichselian, i.e. for the Oerel and Glinde interstadials (cf. Fig. 3). At and beyond 60 ka B.P., however, there are considerable deviations between the terrestrial and deep sea-based chronology. One has always to keep in mind that there are different clocks involved and that direct comparisons are problematic. As regards the difference in the ^{14}C dates for the end of the Early Weichselian (late Odderade), i.e. 61 and 74 ka B.P. from terrestrial and deep sea sediments, respectively, several explanations may be proffered. There are the inherent inaccuracies in the radiocarbon method which, obviously, are particularly acute at the lowermost end of its time range, the high sensitivity to contamination even if only very low levels are involved, and, furthermore, there is no reliable means of calibrating the radiocarbon measurements and making the important conversion to calendar years.

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